4482 Element Multispectral Hybrid PV/PC HgCdTe IRFPA for High Resolution Coverage of 3.7 - 15.4 µm for the AIRS Instrument

James Rutter, Scott Libonate, Brian Denley, Mark N. Gurnee, Gene Robillard, Anthony Sofia, and Jim Stobie

Lockheed Martin IR Imaging Systems
Lexington, Massachusetts 02173

ABSTRACT

The Atmospheric Infrared Sounder (AIRS) is a key facility instrument in the NASA Earth Observing System (EOS) program, being implemented to obtain comprehensive long-term measurements of earth processes affecting global change. The instrument performs passive IR remote sensing using a high resolution grating spectrometer with a wide spectral coverage (3.7 - 15.4 µm) directing radiation onto a hybrid HgCdTe IRFPA operating at 58K in a vacuum package cooled to 155K.

The hybrid HgCdTe FPA consists of twelve modules, 10 with multiplexed photovoltaic detectors and two with individually leaded out photoconductive detectors. The complex FPA has a large optical footprint, 53 mm x 66 mm, and receives energy dispersed from the grating through a precision filter assembly containing 17 narrow band filters. The backside illuminated PV detector arrays are fabricated from P-on-n double layer LPE grown heterojunction detectors in a bilinear format of 50 µm x 100 µm detectors, with from 232 to 420 detectors per module. For the MWIR bands four PV modules cover the 3.7 µm to 8.22 µm region. Low detector capacitance and low noise preamplifiers in the ROIC are key to achieving high sensitivities in these bands. Uniform quantum efficiencies and detectivities exceeding 3E13 cm-rtHz/W have been achieved. The LWIR region is covered by six PV modules spanning 8.8 µm to 13.75 µm. High detector resistance and very low ROIC preamplifier input noise are key to achieving high sensitivity. A detectivity exceeding 2E11 cm-rtHz/W has been achieved at the longest wavelength. Two additional PC modules cover the longest spectral bands out to 15.4 µm.

This high performance multispectral focal plane has been built and integrated with the dewar assembly, and is currently being integrated with the complete AIRS sensor.

INTRODUCTION

Today's sophisticated weather forecasting models have requirements for data inputs which exceed the limited spatial, altitude, and temperature resolution of current infrared instruments employed for atmospheric and earth observing sciences. To fill this gap, the AIRS project has been funded by NASA to take advantage of recent detector technology advances to develop a high resolution IR spectrometer instrument for the Earth Observing System[1]. It will collect data which will allow generation of global surface temperature maps with 0.5K accuracy, tropospheric temperature profiles of 1K accuracy in 1km thick layers to an altitude of 25 km, and will collect information about atmospheric aerosols which will be used for application in weather prediction and global change studies. Surface temperatures are obtained through atmospheric transmission windows. Emission line ratios of CO_2, and absorption bands of H_2O are the primary atmospheric constituents that will be used to infer temperature and humidity profiles. This new instrument will dramatically improve the resolution matrix, enhance the accuracy of these weather models, and aid in the understanding of airborne aerosols, and their impact on global climate.

The AIRS instrument is a high resolution multi-aperture IR echelle spectrometer with a nominal spectral resolution (l/Dl) of 1200. The radiant energy from the Earth is directed from the scan mirror through a multi-aperture slit containing one set of narrow band entrance filters, to a diffraction grating which disperses the filtered energy onto the focal plane array (FPA) though a final set of order sorting filters as shown pictorially in Figure 1. The instrument is described in greater detail in Rutter et. al.[2].

The spectrometer operates at 155K to reduce the shot noise from the background radiation and is cooled by a two-stage radiant cooler. The FPA resides inside a large custom evacuated dewar shown in Figure 2 which accommodates the electrical leads required to operate the FPA, and which is in turn precision mounted into the

spectrometer. The FPA can be cooled to between 55 and 65K (58K nominal) via a sapphire rod which connects the dewar endwell to a Stirling pulse-tube cooler [3].

A photograph of the multi-spectral focal plane for the AIRS infrared spectrometer is shown in Figure 3. The focal plane covers 15 spectral bands over the range from 3.74 - 4.61 μm, 6.20 - 8.22 μm, and 8.80 - 15.4 μm. These bands are distributed among 12 modules. The two longest wavelength modules consist of direct leadout PC HgCdTe detectors, and the remaining modules are PV HgCdTe detectors coupled to CMOS readout integrated circuits (ROICs). The central four modules cover the grating wavelengths less than 8.22 μm and are designated MWIR modules. The remaining six modules covering wavelengths from 8.22 μm to 13.6 μm are the LWIR modules.

The 12 modules are bonded to daughter boards which are in turn bonded to an eighteen-layer motherboard which routes the electrical signals out to the dewar feed-throughs via custom tape cables. The motherboard and flex cables were designed to reduce electromagnetic interference and module-to-module crosstalk. The design and layout of this complex motherboard took into account not only spectral partitioning, but also size constraints imposed by array and readout integrated circuit (ROIC) fabrication limitations, thermal stress issues, and electrical lead out and fan out issues.

The individual PV detector elements are 50x100 μm on a 50 μm pitch. Two adjacent PV detectors in the cross-dispersed direction form a single spectral sample, enhancing sensitivity and providing some protection against detector outages. In addition, each half of the bilinear detector array is driven by an independent set of circuits in the ROIC to give redundancy for graceful degradation. Two adjacent spectral samples in the dispersed direction form one spectral resolution element, providing Nyquist sampling.

MODULE DESIGN AND PERFORMANCE

Sensitivity and resolution over the entire IR band is of critical importance in meeting the AIRS mission requirements. Achieving the highest possible sensitivity in each band required careful attention to detector characteristics and careful design of each of the ten different ROICs. Readout of MW detectors requires extremely high gain transimpedance amplifiers. The charge sensitive input amplifiers on these readout devices utilize an equivalent input integration capacitor of less than 10 fFd to achieve ultrahigh transimpedance gain, and reset noise is suppressed with on-focal plane correlated double sampling. LWIR readouts use low noise buffered direct injection input circuits, with ultralow noise amplifiers for the longest wavelength bands. The temporal frequency over which the modules must operate is 0.1 to 22.4 Hz, so special attention has been paid to low detector and ROIC noise at low frequencies. The readouts have a robust architecture with differential input and outputs to minimize EMI and built in redundancy for survivability.

Detectors

The operating temperature of the focal plane is 60 K, chosen as a balance between cooler size weight, power and life, and IRFPA performance. At this temperature the detector electrical characteristics are important inputs to the design success. The detector capacitance is important for low noise coupling to MW detectors. Over the MWIR bands the detector capacitance varies from 0.5 to 1.0 pf. The R_oA product at the shortest wavelength can be shunt limited to as low as 100 Mohms-cm2 and still provide low noise detector performance. As the detector spectral band is increased, the R_oA product capability decreases by 7 orders of magnitude. This behavior is also reflected in the dark currents for nominally biased detectors. For all except the longest wavelength PV spectral band, the background current at the nominal background flux is higher than the detector's dark current.

Detector arrays with 4.7 mm cutoff wavelength at 60 K and 20 mV reverse bias have R_dA values typically greater than 10^{10} ohm-cm^2, with dark signals less than 0.6 fA and detector capacitance's less than 0.6 pf for a 50 μm by 100 μm detector. AR coated MW arrays exhibit quantum efficiencies of greater than 80 percent. Reverse breakdowns are more than -150 mV. Module data for 15.1 μm detectors with anti-reflection coating exhibit quantum efficiencies greater than 70 percent and dark currents less than 8 nanoamps at 20 mV reverse bias. Also, excellent module linearity meeting the AIRS stringent requirements is achieved.

ROICs

Four basic circuit types with ten different gain and integration capacitor combinations were employed in the PV module ROICs to accommodate the wide range of scene and background fluxes in the 15 spectral bands[4]. Charge integrating differential amplifiers (CIDA) with correlated double sampling (CDS) circuits to reduce reset noise were chosen for the shortest wavelength modules M1 and M2. At longer wavelengths, reset noise is no longer an issue, but instrument background dominates the scene flux, so modules M4 through M10 use a dynamic DC restore (DCR) circuit that passes only the scene content to limit the output dynamic range to only the signal value. Modules M3 and M4 have CIDA inputs with this DCR function. Modules M5 through M10 incorporate buffered direct injection inputs (BDI) with the DCR function, with M9 and M10 requiring a particularly low noise BDI approach to accommodate the low detector impedances at the longest PV wavelengths.

The ROICs must operate within the EMI environment of the satellite and deliver the detector signal without loss of fidelity to the warm external electronics over a cable approximately three feet in length. Self-induced EMI signals that cross couple to other modules are as much of a concern as externally generated sources. To mitigate the effects from unwanted signals, a moderately high output noise floor of greater than 1 mVrms was established. Complementary clocks and output buffer line drivers with low output impedance are included to minimize noise pickup. Control commands are sent to the ROIC encoded on the biphase pixel clocks. Programmable functions include the start and duration of each integration cycle, selection of discrete on-chip detector biases, and other optional modes of operation. To minimize lead count and still provide complete redundancy, i.e. independent autonomous operation for each side of the bilinear arrays, each module uses two redundant supply leads and their returns, and two redundant differential clock pairs.

The active power for the 10 PV modules is less than 120 mW with a collective data rate more than 3 megasamples per second.

FPA Test Station

The FPA test stations have been designed to accommodate the requirements of the four levels of testing from ROIC wafer probe through cold testing of flight-candidate ROICs, to module and FPA test for the ten types of PV ROICs/modules with minimal hardware modifications. The test stations can be quickly re-configured for wafer probe, ROIC cold test, or module test, enabling a quick response to scheduling demands and maximizing test throughput. An HP9000-382 running custom AIRS test software controls the test station over an IEEE-488 interface. A waveform generator and bias supply provide the necessary clocks and biases to the unit under test (UUT) through a custom interface box. The FPA test dewar uses a combination of cold nitrogen and helium gas transfer to cool the FPA flight dewar to 155K while allowing the focal plane to reach the 55 to 65K range. Wide area blackbody radiation sources have a pneumatically controlled shutter/aperture mechanism with a cold shutter and four aperture selections (nominally f/100, f/40, f/30, and f/20) so that the instrument scene flux ranges can be sampled. A cold (~80K) narrow band filter mounted inside the dewar directly above the UUT blocks all out-of-band radiation. The instrument background for each band can be simulated with an additional temperature-controllable blackbody located inside the test dewar between the shutter and the UUT.

Module Performance

At the very short wavelength end, the sensitivity is limited by the 1/f noise of the CIDA stage. At the other extreme in wavelength, the sensitivity is limited by the detector thermal noise and input preamplifier 1/f noise. The sensitivity requirements of each of these bands places special constraints on the ROIC circuitry and detectors.

For the shortest MWIR band the critical detector requirement is on its capacitance; the RoA requirement to insure that the detector Johnson noise is lower than the background noise is readily met. A large detector capacitance relative to the very small feedback capacitance in the CIDA input circuit increases the circuit gain to its internal amplifier noise which can spoil the noise figure of the input. As the detector capacitance increases so does the noise gain for the CIDA preamplifiers. The detectors were specifically designed for low capacitance; the measured capacitance for detectors with a cutoff wavelength of 4.7 mm at 60 K averages about 0.6 pf. Furthermore, the average capacitance of these detectors is reduced by as much as 20 percent with a reverse bias of -120 mV. Thus operation at a high reverse bias, more than -100 mV, is desirable for the MWIR modules. The effect of detector

capacitance on M1 module noise performance is shown in Figure 4, along with the achieved detector capacitance. It is evident that excellent noise performance is obtained with a low detector capacitance.

For the longest LWIR band the critical requirements are on the detector's resistance at its operating bias in combination with the low frequency noise voltage of the input amplifier. This dependence is shown in Figure 5, along with the performance obtained with the achieved low amplifier input 1/f noise at 1 Hz. The ROIC input amplifiers were designed with large area input transistors to achieve this low noise.

The linearity of the modules must meet stringent requirements. The deviation from linearity is specified as $\pm$3 percent of the absolute scene flux, exclusive of background over most of the scene range. For large scene fluxes this is a liberal requirement, but at low flux levels this becomes a difficult specification to satisfy. The requirement has a breakpoint at extremely low flux levels to prevent a singularity at zero scene flux. The full scale nonlinearity is measured to be less than 0.054 percent for a full 3.8 volts range at the output.

The flowdown specification requires that in addition to basic functionality (i.e. response to commands, proper operation of input cell reset and DC restore, allowable power consumption), modules must have uniform response with QE on the order of 70%, low noise or NEQFD and no outages at science-critical spectral channels (Aumann[1] lines). The testing of modules built for the focal plane has demonstrated that the uniformity, QE, NEQFD, and outage requirements have been achieved.

A summary of the overall performance of all of the twelve modules is shown in Figure 6 with the spectral coverage and the median sensitivity achieved in each band shown as overlays on the relative position of the modules on the focal plane. Quantum efficiency plots for modules M1, M4, M7 and M10 are shown in Figures 7 through 10, and demonstrate that the QE goal and uniformity requirements (max:min response < 2:1) have been met in these four representative modules. The data for both outputs of the bilinear arrays are shown on a single plot. Plots of the module sensitivity (NEQFD) per spectral sample are shown in Figures 11 through 14. Excellent performance meeting the AIRS requirements has been achieved in all bands.

CONCLUSIONS

A very high performance, broad spectral band IRFPA has been built and tested for the Atmospheric Infrared Sounder (AIRS), a key facility instrument in the NASA Earth Observing System (EOS) program. The hybrid HgCdTe FPA consists of twelve modules, 10 with multiplexed photovoltaic detectors and two with individually leaded out photoconductive detectors, covering the spectral range from 3.7 μm to 15.4 μm. Careful design was necessary for both the shortest and the longest spectral bands to achieve the required sensitivity. This high performance multispectral focal plane has been built and integrated with the dewar assembly, and is currently being integrated with the complete AIRS sensor.

ACKNOWLEDGMENTS

The AIRS instrument is being designed and built at Lockheed Martin IR Imaging Systems, Lexington, MA, and is being supported by NASA contract #958970, administered by the Jet Propulsion Laboratory.

REFERENCES

1. Aumann and R.J. Pagano, "Atmospheric Infrared Sounder on the Earth Observing System," Optical Engineering 33, 776 (1994).
2. Scott Libonate, Brian Denley, Eric Krueger, Jim Rutter, Jim Stobie, Lynne Terzis, "*Development Status of the AIRS IR Focal Plane Assembly*" *SPIE Vol.*
3. Rutter, D. Jungkmann, J. Stobie, E. Krueger, J. Garnett, M. Reine, B. Denley, M. Jasmin, and A. Sofia, "A Multispectral Hybrid HgCdTe FPA/Dewar Assembly for Remote Sensing in the Atmospheric Infrared Sounder (AIRS) Instrument", *SPIE Vol. 2817*, Denver, CO, 6-7 August, 1996.
4. Stobie, A. Siegel, J. Rutter and M. Gurnee, "Advanced Readout Circuits for MWIR, LWIR, and VLWIR PV Detector Arrays at 60K," Proceedings of the IRIS Detector Specialty Group Meeting, Bedford, Massachusetts, 17-19 August, 1993.

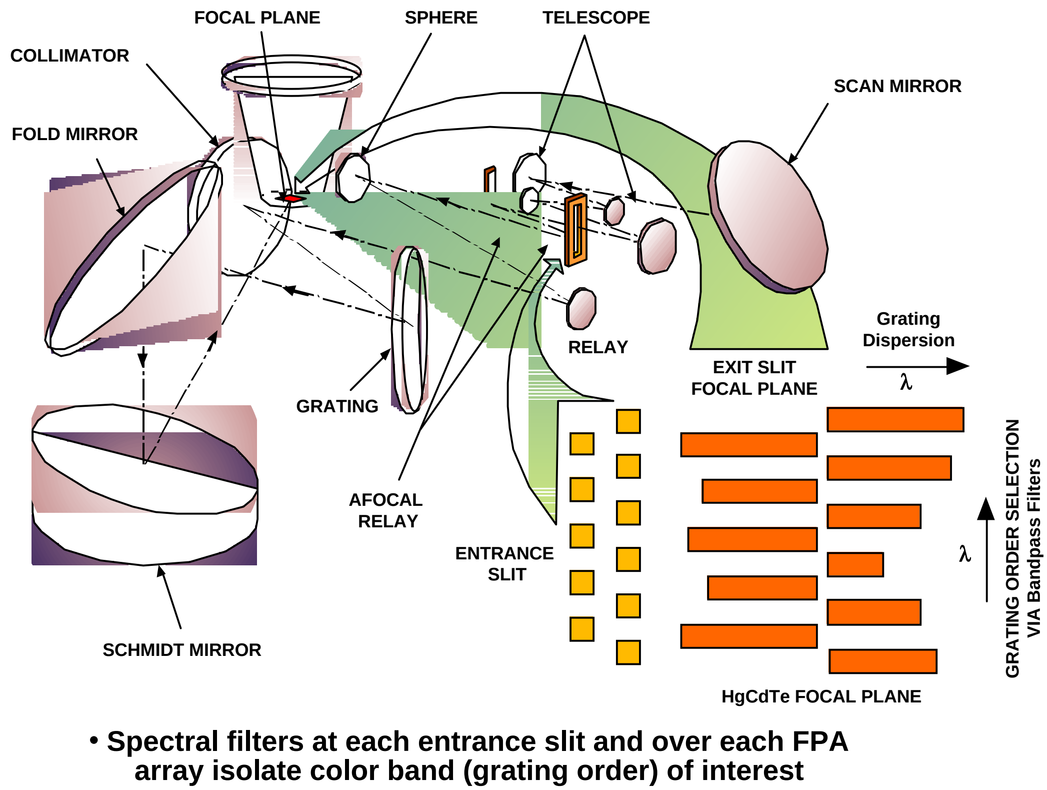

Figure 1. Pictoral Description of the Optical Paths of the AIRS Instrument.

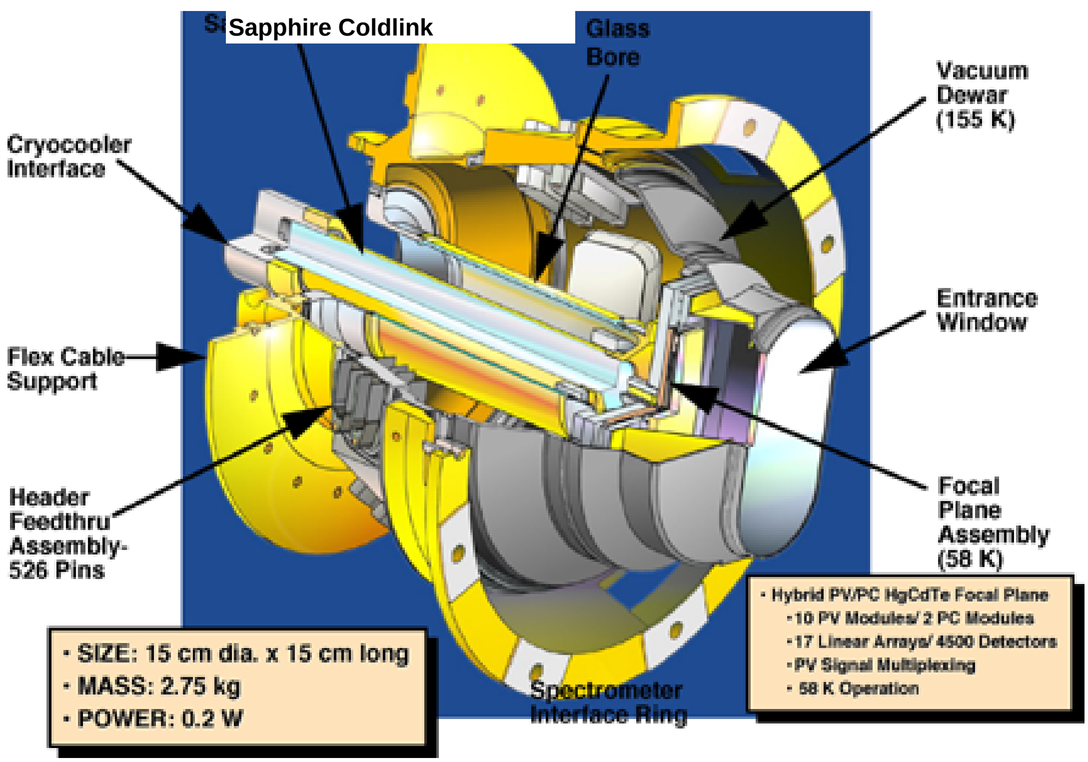

Figure 2. AIRS IR Detector/Dewar Assembly

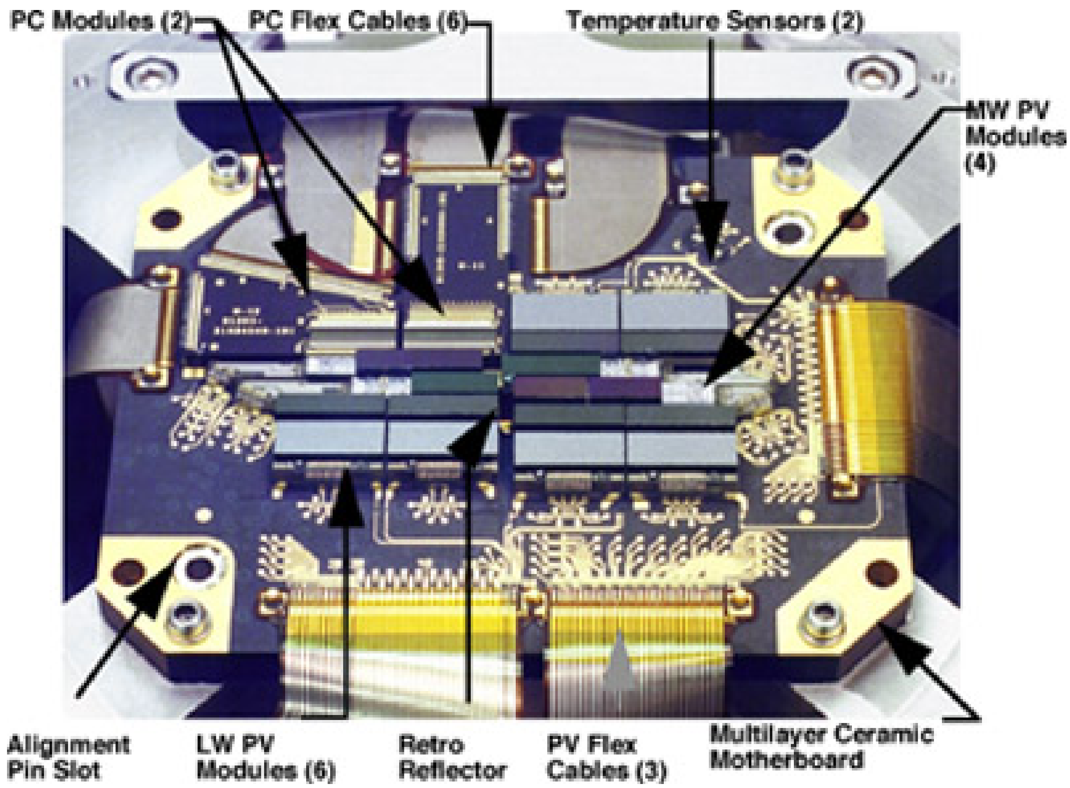

Figure 3. The AIRS Focal Plane Includes Twelve IRFPA Modules Precision Aligned On The Motherboard

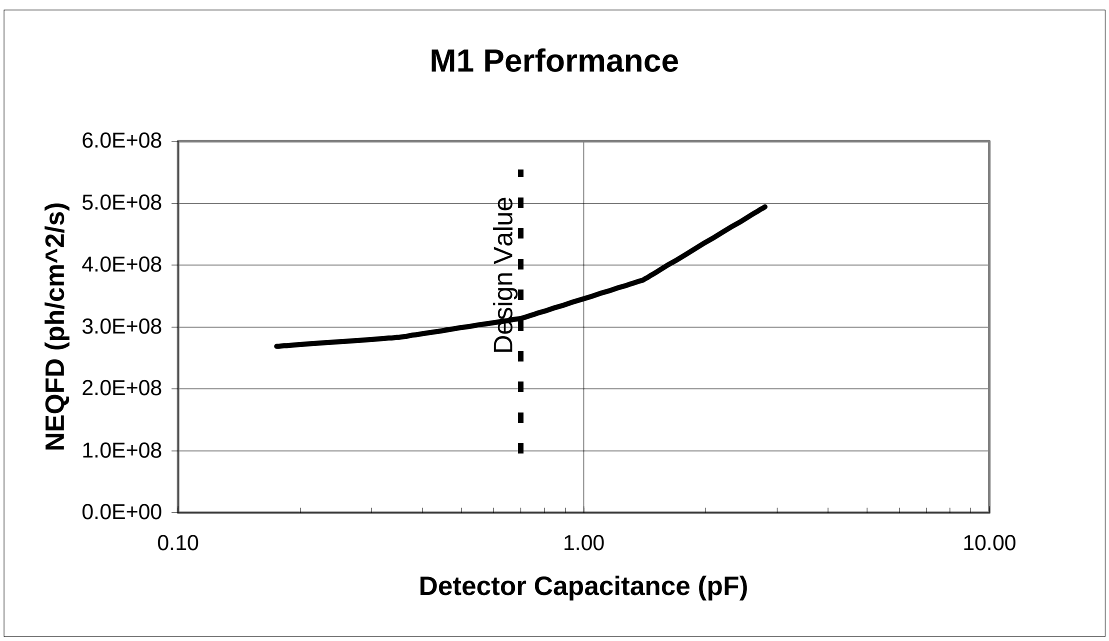

Figure 4. Low detector capacitance is critical to achieving high sensitivity in the shortest wavelength bands.

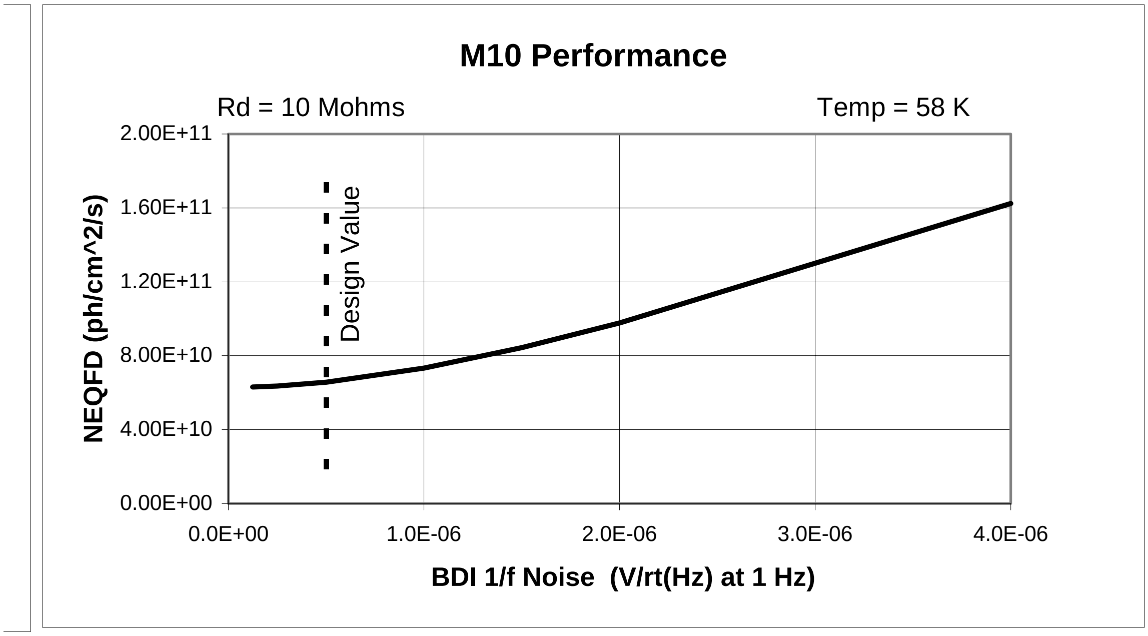

Figure 5. Low Buffer Amplifier Noise And High Detector Resistance Are Critical To Achieving High Sensitivity In The Longest Wavelength Band.

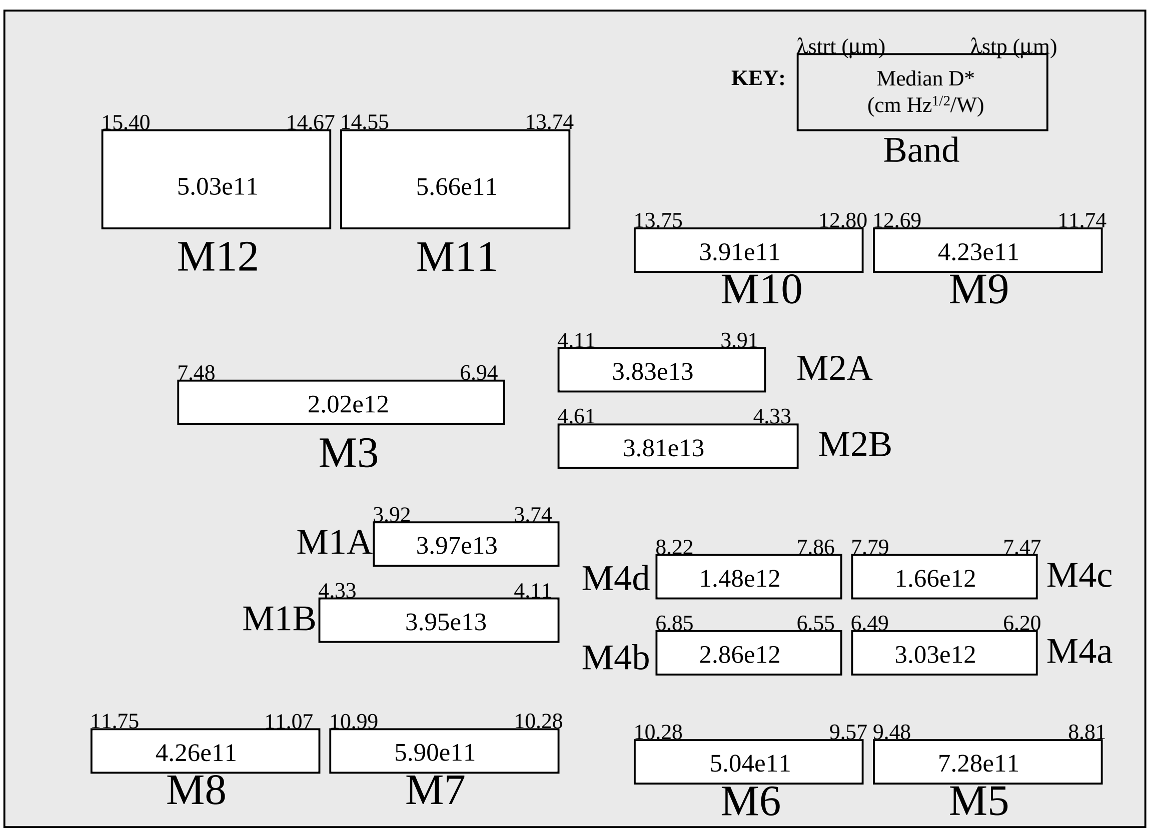

Figure 6. The Overall Performance Obtained On The Entire AIRS FPA Is Excellent. This figure shows schematically the location of each module and its spectral coverage and median sensitivity achieved.

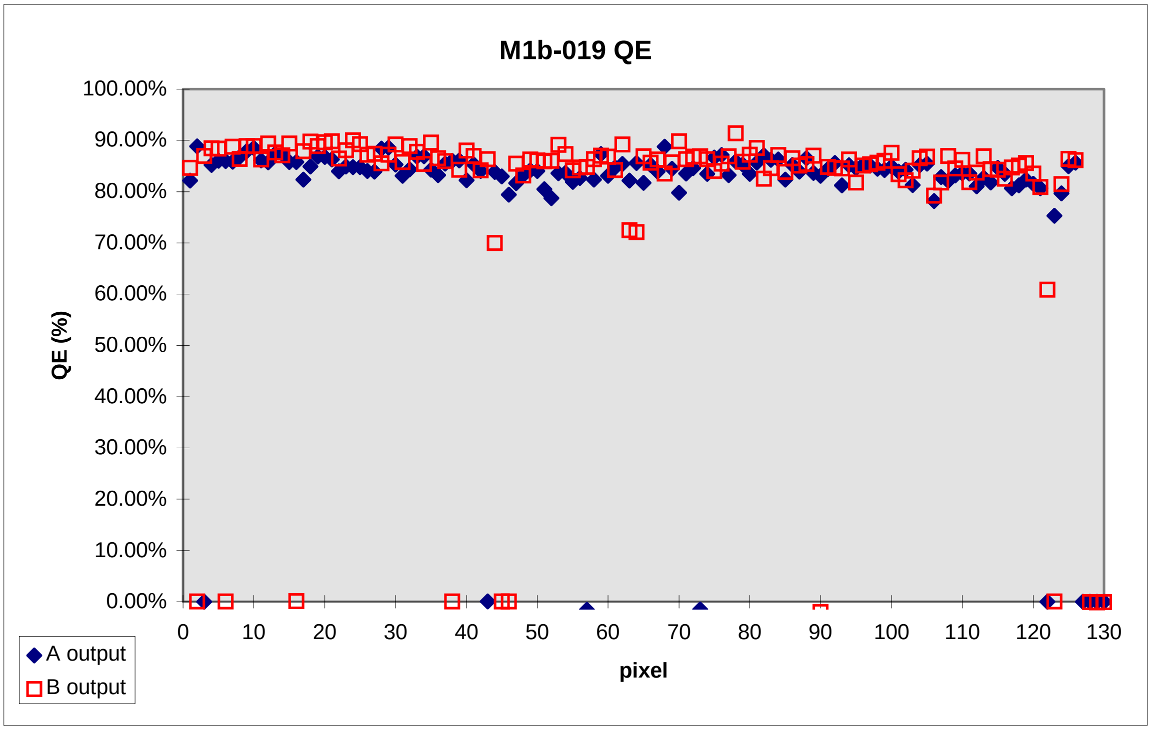

Figure 7. Excellent Quantum Efficiency Has Been Obtained On Detectors Used For Module 1, Sensitive From 3.7 µm to 3.9 µm.

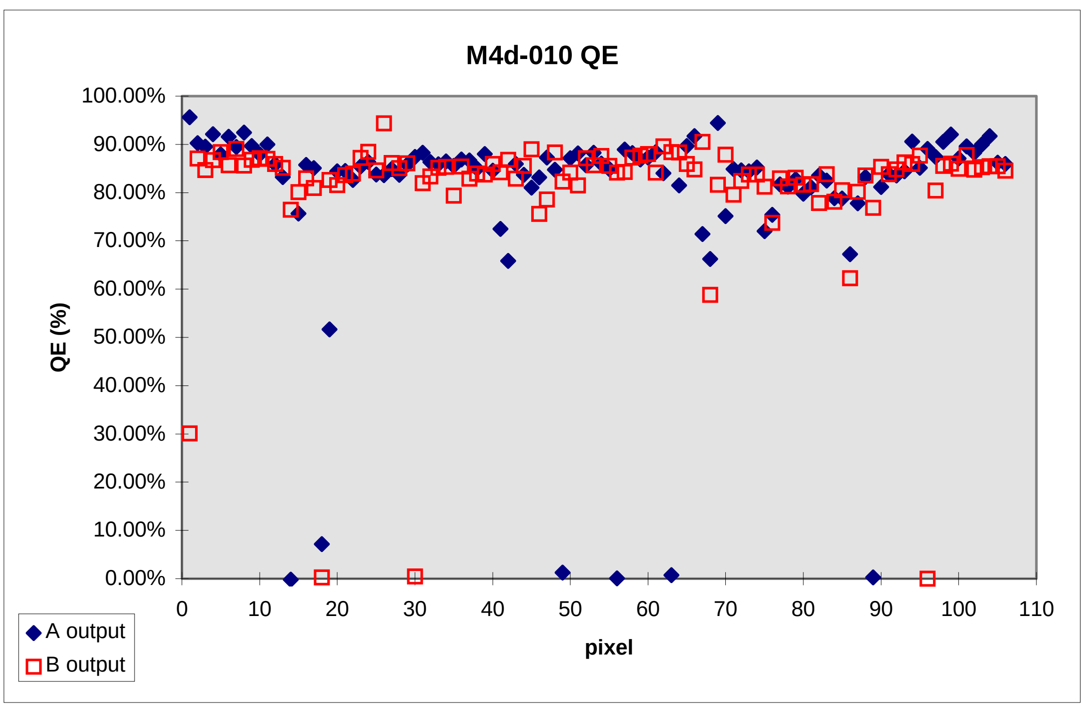

Figure 8. Excellent Quantum Efficiency Has Been Obtained On Detectors Used For Module 4, Sensitive From 4.3 µm to 4.6 µm.

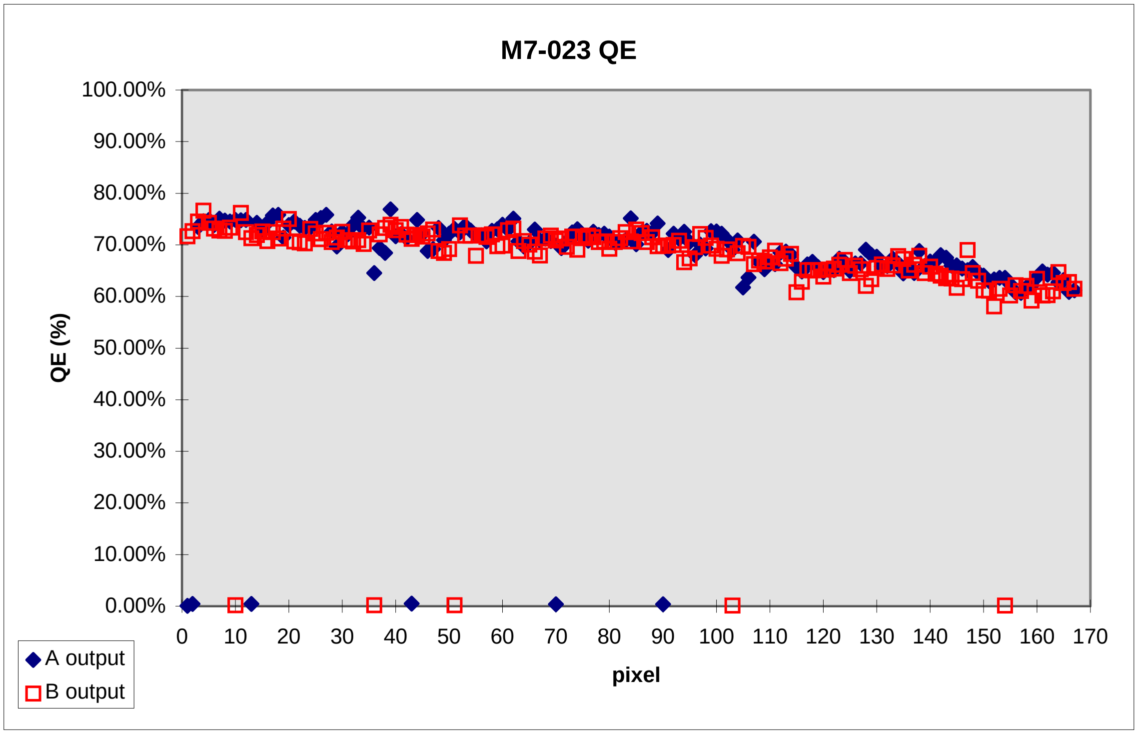

Figure 9. Excellent Quantum Efficiency Has Been Obtained On Detectors Used For Module 7, Sensitive From 6.9 µm to 7.5 µm.

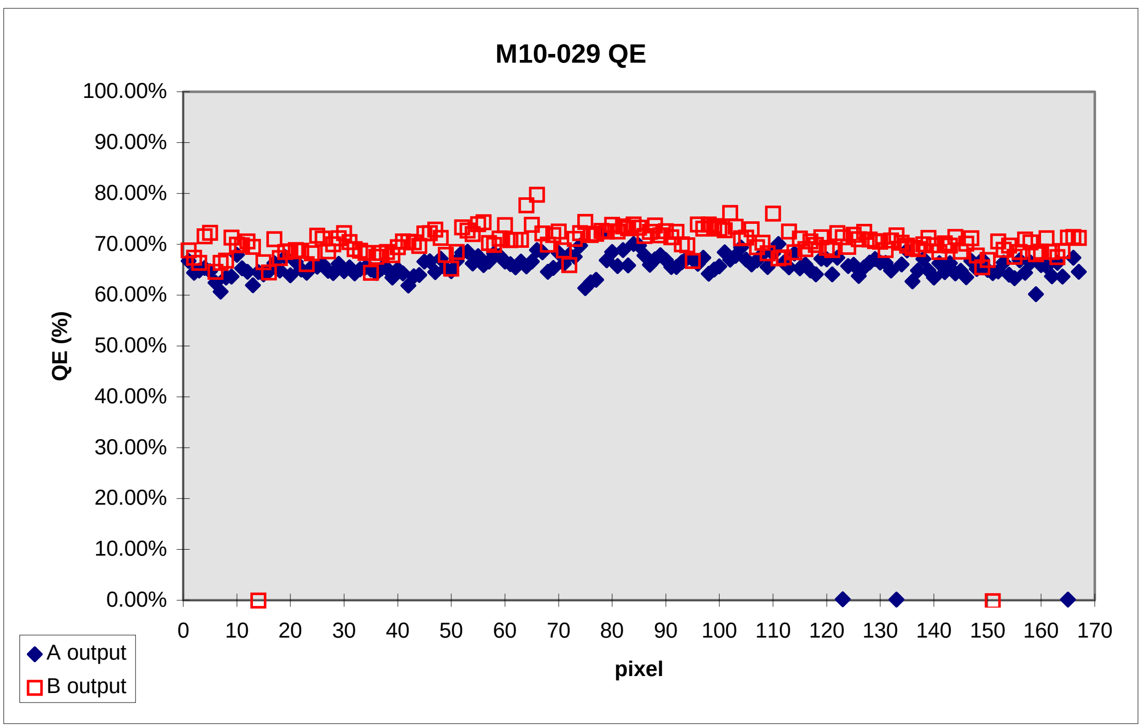

Figure 10. Excellent Quantum Efficiency Has Been Obtained On Detectors Used For Module 10, Sensitive From 12.8 µm to 13.7 µm.

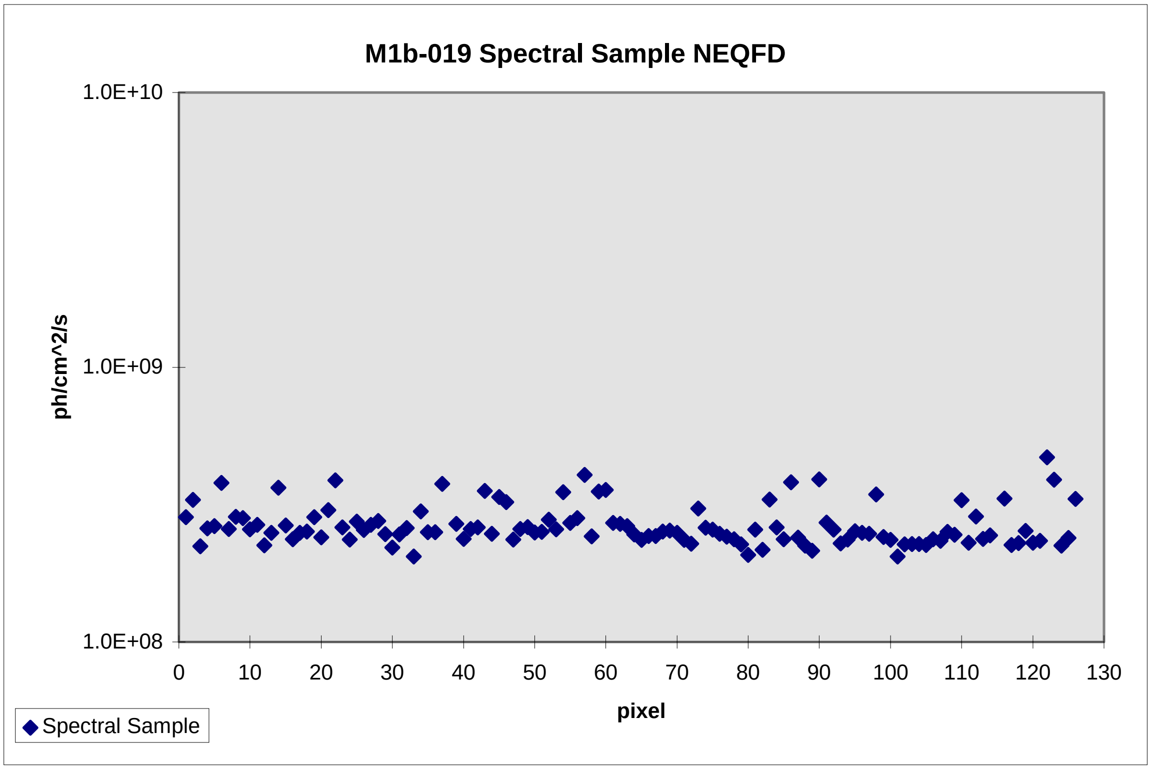

Figure 11. Excellent NEQFD Has Been Obtained On Detectors Used For Module 1, Sensitive From 3.7 µm to 3.9 µm.

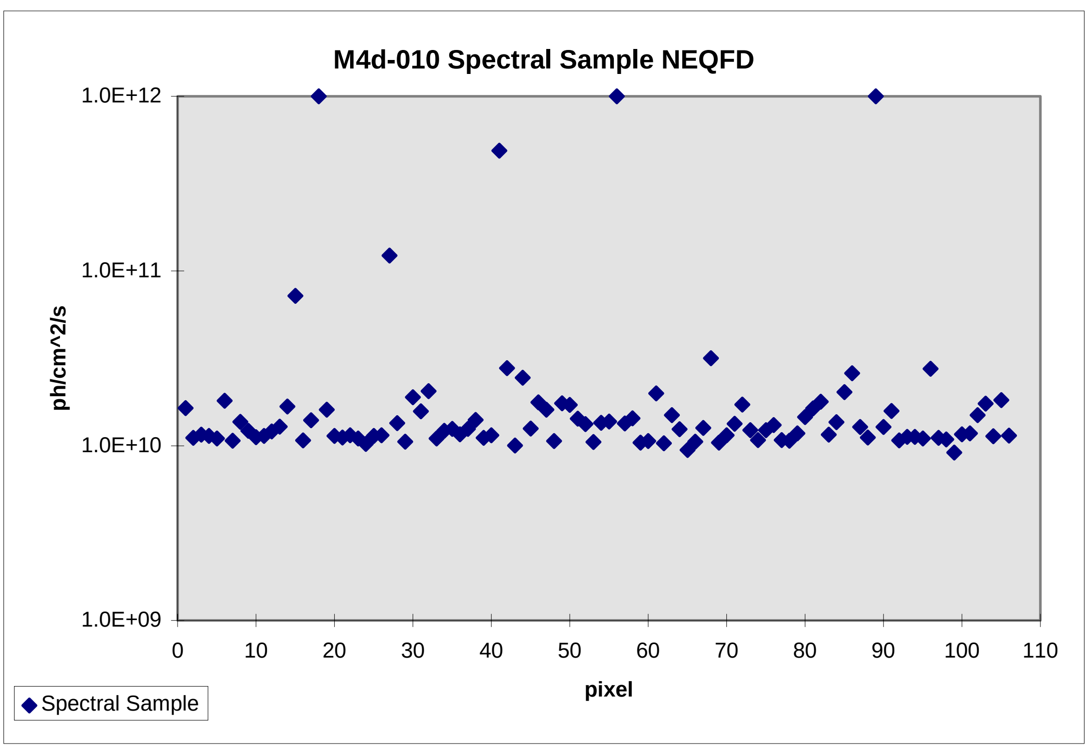

Figure 12. Excellent NEQFD Has Been Obtained On Detectors Used For Module 4, Sensitive From 4.3 µm to 4.6 µm.

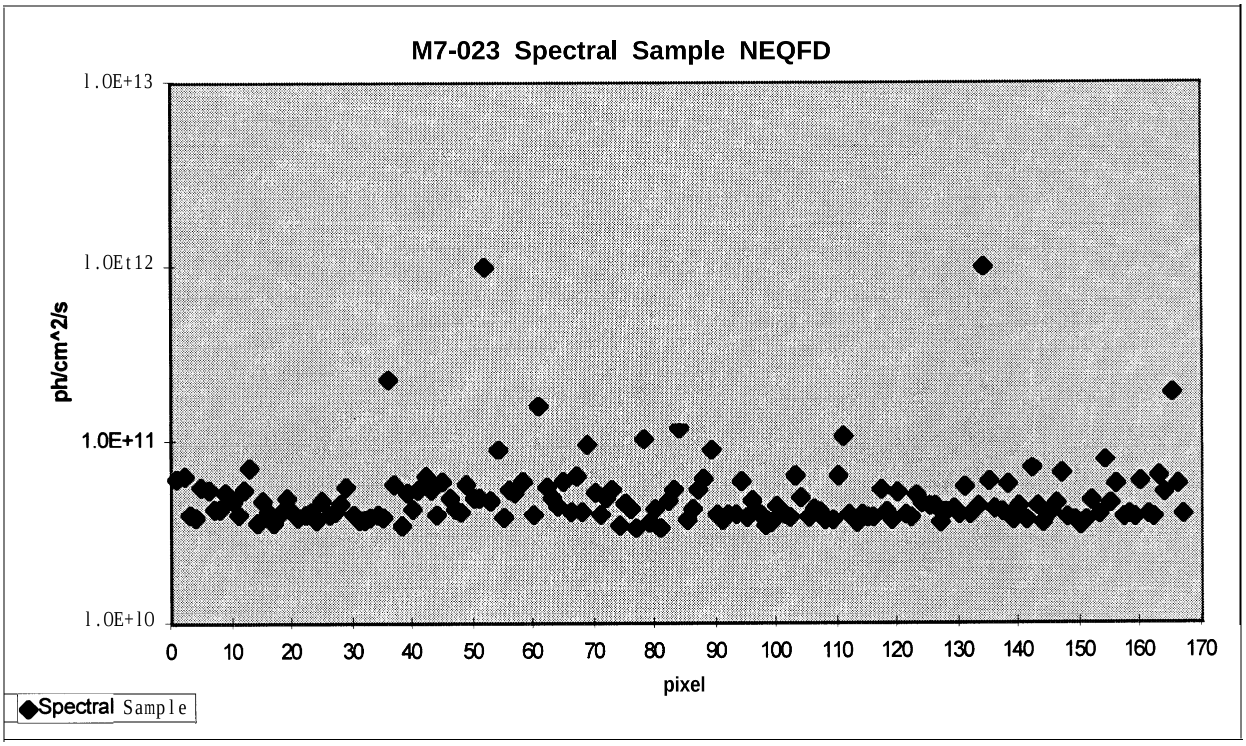

Figure 13. Excellent NEQFD Has Been Obtained On Detectors Used For Module 7, Sensitive From 6.9 µm to 7.5 µm.

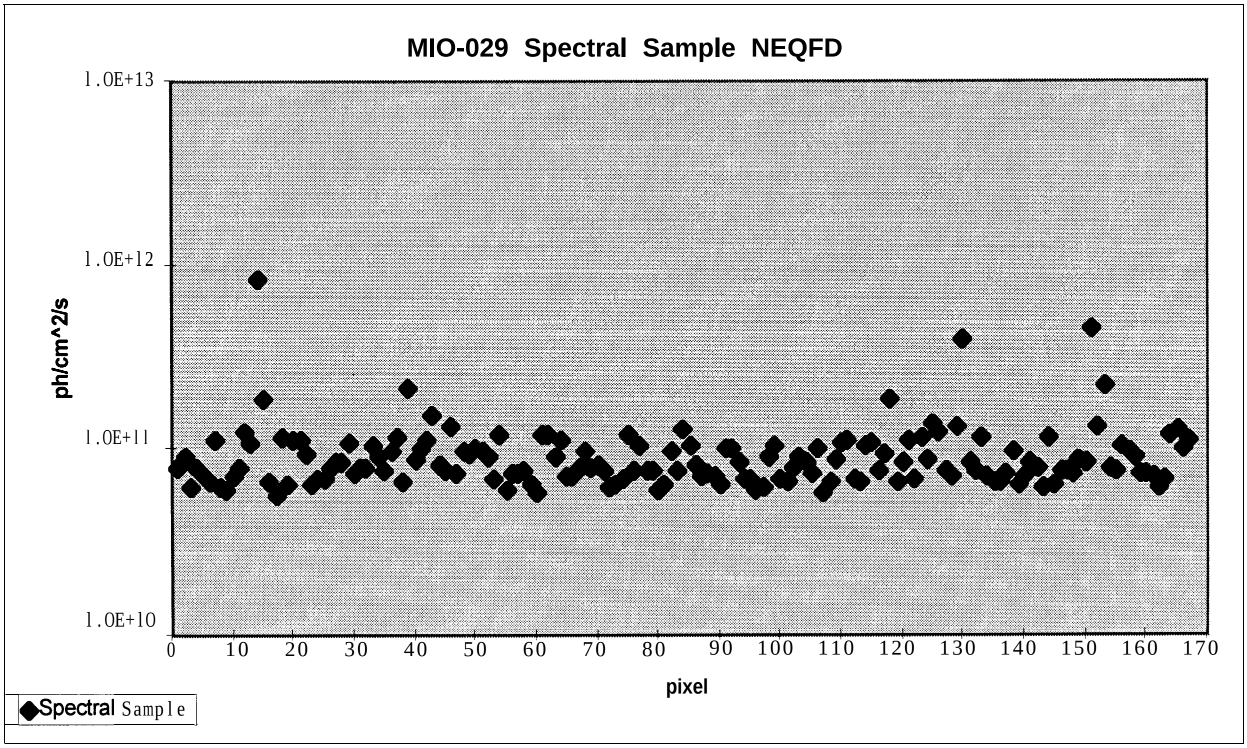

Figure 14. Excellent NEQFD Has Been Obtained On Detectors Used For Module 10, Sensitive From 12.8 µm to 13.7 µm.